Jeremy R. Manning
Dartmouth College
Department of Psychological & Brain Sciences
HB 6207 Moore Hall
Hanover, NH 03755

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To the editors of *Scientific Reports*:

We have enclosed our revised manuscript entitled *Fitness tracking reveals task-specific associations between memory, mental health, and physical activity* (manuscript submission ID: e1b8f4e6-74a0-4e1a-86f5-ce997fea5f44). We appreciate the reviewers' insightful comments on our original submission. We provide a brief summary of our changes on this page, along with detailed point-by-point responses on the following pages. The reviewers' comments are *italicized* and our responses are in **bold**.

Reviewer 1 raised some concerns about the distinction between "exercise" and "physical activity" (suggesting that our approach is more related to "physical activity" than "exercise" given how these terms are described in the current literature). We agree and have adjusted our terminology accordingly. They also raised questions about the clarity of our take-home messages. We have expanded on these in our revised discussion section. Reviewer 2 suggested adding several recent reviews, which we have done. They also suggested some points for clarification and further discussion. As described in our detailed responses, we have addressed each of both reviewers' concerns.

Thank you for considering our revised manuscript.

Sincerely,

Jeremy R. Manning
Jeremy.R.Manning@Dartmouth.edu

Reviewer 1

To the authors. The authors state in their abstract that they intend to focus on how specific forms of exercise relate to different aspects of memory and mental health. Specialists in the field of kinesiology would probably conclude that the authors did not truly address their primary question. Kinesiologists agree that exercise can be categorized in terms of Frequency, Duration, Intensity, and Mode. As described on page 10, the authors describe fitbit data in terms of "heart rate data, sleep tracking data, logged bodyweight measurements, logged nutrition measurements, Fitbit account and device settings, and activity metrics." On Page 11, the authors detail the heart rate measures provided via fitbit. "These summaries include information about participants' average heart rates, and the amount of time they were estimated to have spent in different "heart rate zones" (rest, out-of-range, fat burn, cardio, or peak, as defined by their Fitbit profile)." The data analyzed provides information concerning the intensity of physical activity. The data analyzed do not capture differences in exercise as a function of mode (e.g., running, cycling, resistance training exercise, complex skill-training exercise). As such, the authors fall short on answering questions concerning forms (types) of exercise.

Specialists in kinesiology also agree on the differentiation between the terms physical activity and exercise. Physical activity reflects any change in muscle activation; whereas, exercise is performed with the intent to improve one or more of the components of physical fitness: Muscular strength, muscle endurance, cardiovascular capacity and flexibility. It could be argued that the data obtained by the authors relate more to physical activity than exercise (which is in the title of the manuscript).

We appreciate the reviewer's point that our use of the term "exercise" in our manuscript often conflicts with its more common uses in the broader literature (e.g., the kinesiology literature that the reviewers references). As the reviewer notes, our study is more focused on "physical activity" (specifically, on the *intensity* of physical activity, as inferred through heart rate measurements). To this end, throughout our revised manuscript (including our title and abstract), we have updated our use of the terms "exercise" and "physical activity" to more closely align with the reviewer's suggestions. We have also updated our phrasing throughout the manuscript to clarify that we are examining the intensity (rather than "type") of physical activity our participants engaged in.

There are strengths to the manuscript. The authors provide a well-designed and comprehensive study of the relation between field-based measures of physical activity and performance on a battery of cognitive tests. The large sample size, the quality of testing methods, and sophisticated statistical analyses are recognized.

We appreciate the reviewer's positive feedback.

Despite the quality of the laboratory methods and statistical analyses, the conclusions and "take home messages" are quite weak. In what way do the data support contemporary theories that attempt to explain the relation between physical activity/exercise on cognition, information processing, or mental health? Likewise, if the authors are attempting to influence exercise professionals, how might the results impact intervention design? If the authors and

focusing on dissemination of their findings to academics in the field of kinesiology and exercise science, what specific recommendations could be provided?

We see our study as contributing three main take-home messages:

- **Most prior (primary) studies treat exercise or physical activity as a "binary" variable that participants either engage in (e.g., in an "exercise" or "training" condition) or do not engage in (e.g., in a "control" condition). Our work suggests that the true relations between physical activity, cognitive performance, and mental health may be substantially more complex (e.g., non-monotonic, multivariate, etc.).**
- **Most prior work has tracked or manipulated exercise or physical activity over relatively short timescales (on the order of days or weeks). Our work shows that the "true" relations between physical activity, cognitive performance, and mental health may unfold over much longer timescales (on the order of at least several months).**
- **We also show that the relations we identified (between physical activity, cognitive performance, and mental health), while complex, are remarkably stable across individuals. For example, many of the patterns we found were consistent across more than 97.5% of 10,000 randomly chosen subsets of our participants (per our statistical framework, greater than or equal to 97.5% agreement corresponds to a bootstrap-estimated two-tailed p-value of 0.05 or less; also see p. 12–13).**

We have added a paragraph to the discussion section to this effect (p. 23–24):

> **"A number of prior studies have shown that engaging in exercise can improve cognitive and mental health (Taylor et al. 1985, Raglin 1990, Pauluska and Schwenk 2000, Brisswalter et al. 2002, Callaghan 2004, Etnier et al. 2006, Deslandes et al. 2009, Herring et al. 2010, Chang et al. 2012, Basso and Suzuki 2017, Gordon et al. 2017, Mikkelsen et al. 2017, Morres et al. 2018, Morres et al. 2022). The majority of these studies ask participants in an "exercise intervention" condition (where participants engage in a designated physical activity or training regimen) or a "control" condition (where participants do not engage in the designated activity or training) to perform cognitive tasks or undergo mental health screening. In other words, most primary studies treat "physical activity" as a binary variable that either is or is not present for each participant. Most prior studies also track or manipulate exercise over relatively short durations (typically on the order of days or weeks). Our current work indicates that the true relations between physical activity, cognitive performance, and mental health may be non-monotonic and heterogeneous across activities, tasks, and mental health measures. These relations can also unfold over much longer timescales than have been previously identified (on the order of months; Fig. 6). However, despite the complexities of the structures of these associations, we also found that they were often remarkably consistent across people. For example, as displayed in Figures 5 and S14, many of the associations between fitness, behavioral, and mental health measures were consistent across over 97.5% of 10,000 randomly chosen subsets of participants."**

We see our work as informing the *testing* or *development* of theories or recommendations for researchers and practitioners, rather than as pointing to specific interventions as being "best" in a given situation or scenario. For example, our study does not attempt to causally manipulate exercise, so we cannot distinguish correlations between different measures from causal associations. For this reason, we felt it appropriate to refrain from attempting to make specific recommendations about causal activity-based interventions.s

I commend the authors on their work and encourage them to continue their research on the topic. I hope they find my comments to be useful

We thank the reviewer for their encouragement and for their useful comments.

Reviewer 2

The ms entitled "Fitness tracking reveals task-specific associations between memory, mental health, and exercise" is an interesting piece of work.

We thank the reviewer for their positive feedback.

Below comments on the ms.

pls include more up to date evidence regarding the antidepressant and anxiolytic effects of exercise, you can consider the following recent reviews which deal with some of the most typical types of mental health disorders in health services including major depression, perinatal depression, anxiety disorders and a series of mental health variables.
https://onlinelibrary.wiley.com/doi/abs/10.1002/da.22842
https://pubmed.ncbi.nlm.nih.gov/28819746/
https://www.sciencedirect.com/science/article/abs/pii/S0165032721011150
https://jamanetwork.com/journals/jamainternalmedicine/fullarticle/774421

We have incorporated references to and discussion of these studies as recommended (p. 2, 23).

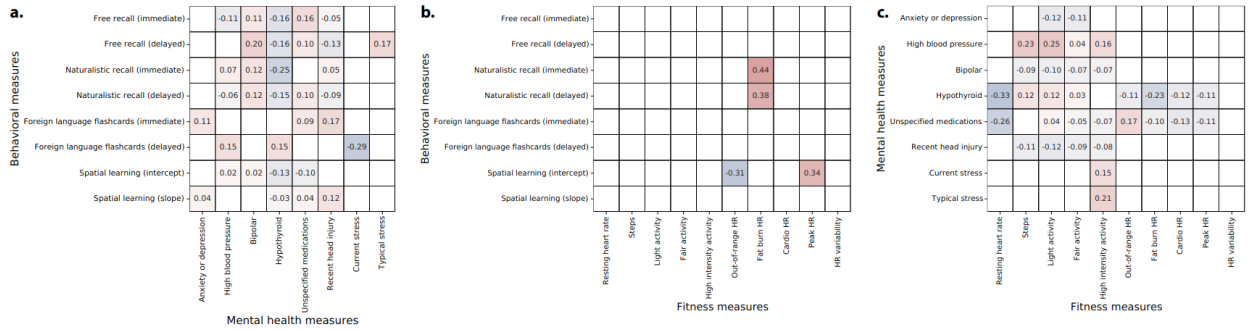
Also, I have the impression that a correlation matrix (such as figure 5) with physical activity and mental health measures should be included in the main ms. If only trends are available, you can illustrate numbers in boxes in different colors.

We have updated Figure 5 as follows:

- **Figure 5 from our previous draft is now Figure 5a. It displays correlations between behavioral and mental health measures.**

- **Figure 5b in our revised manuscript displays correlations between physical activity and mental health measures (as requested).**
- **We have also added an additional panel, Figure 5c, that displays correlations between physical activity and behavioral measures.**

For convenience, we have pasted the revised figure below:



Note that, in generating these new figures, we re-ran our statistical analyses. Because the analysis relies on random sampling, the results differ slightly each time the analysis is re-run. This led to some minor changes in the values reflected in Figure 5a (that had been reported in Fig. 5 of our previous draft) and in the corresponding text of the results section.

In addition, it would be helpful for readers to know whether negative or positive correlations suggest better or worse relationships between variables, for example not always clear if better mental health is associated with more physical activity.

We thank the reviewer for pointing out this oversight. In characterizing our participants' cognitive performance, we adjusted all scores as needed so that larger (more positive) values indicate better performance. Our fitness-related measures (e.g., Fig. 4 and Tab. S1) vary in valence– for example, higher (more "positive") resting heart rate can be indicative of *worse* physical fitness, whereas a larger (more positive) number of minutes spent in high heart rate zones can be indicative of higher levels of physical activity. Finally, for our mental health measures, higher scores denote *worse* (more severe) mental health challenges (e.g., higher reported levels of stress, etc.). We have added notes to this effect to the caption of our revised Figure 5, where we report correlations between all three types of measures. We have also attempted to clarify the associated text in our Results section (p. 21).

Regarding the reviewer's last comment (with respect to clarity around whether better mental health is associated with more physical activity), we find that the relation between physical activity and different mental health measures is more complex than this sort of binary association. For example, as shown in our revised Figure 5c, more active participants (i.e., higher step counts, longer durations spent in each activity zone) also tended to have higher blood pressure, which can be indicative of higher levels of stress. (We examined the *dynamics* of the relation between stress and activity in Fig.

6c.) On the other hand, higher levels of some aspects of physical activity were associated with *better* mental health. For example increases in light to fair (medium) intensity activity were associated with lower anxiety and depression (consistent with prior work). In general, we found that most fitness measures (columns of Fig. 5c) had heterogeneous correlations with mental health measures (rows of Fig. 5c). In other words, most columns in Figure 5c display a mix of blue (negative correlations) and red (positive correlations) squares. For example, participants who engaged in more high-intensity activity tended to have higher blood pressure, be less likely to be bipolar, and more likely to report high stress levels.

Finally, it is not clear whether the stress, sleep and other mental health scales have been previously standardized.

The stress, sleep, and mental health scores we report are all described in the *Methods* section (p. 4–6, 10–13). Since we obtain only one value for each of these measures, we cannot standardize these scores within-participant. However, since each of these scores is on the same "scale" across participants (e.g., the number of hours of sleep is reported in the same units across people), we feel justified in examining the "raw" (un-normalized or standardized) values in our analyses.

One exception is that some of our analyses entailed estimating "baseline" scores and comparing them to more recent values. Our procedure for baselining the data is described on p. 12. In brief, for each measure, we divided the average measurements taken over the past 7 days by the average measurements taken over the 30 days prior to that. This yielded an adjusted score for each participant that attempted to highlight recent similarities and differences in the relevant measurements.

An overall comment, I think the discussion should become larger and reflect more on the relationships between mental health and physical activity.

Reviewer 1 made a similar comment, and we have expanded our discussion section by adding the following paragraph (copied from our response to reviewer 1 for convenience; p. 23–24):

> **"A number of prior studies have shown that engaging in exercise can improve cognitive and mental health (Taylor et al. 1985, Raglin 1990, Pauluska and Schwenk 2000, Brisswalter et al. 2002, Callaghan 2004, Etnier et al. 2006, Deslandes et al. 2009, Herring et al. 2010, Chang et al. 2012, Basso and Suzuki 2017, Gordon et al. 2017, Mikkelsen et al. 2017, Morres et al. 2018, Morres et al. 2022). The majority of these studies ask participants in an "exercise intervention" condition (where participants engage in a designated physical activity or training regimen) or a "control" condition (where participants do not engage in the designated activity or training) to perform cognitive tasks or undergo mental health screening. In other words, most primary studies treat "physical activity" as a binary variable that either is or is not present for each participant. Most prior studies also track or manipulate exercise over relatively short durations (typically on the order of days or weeks). Our current work indicates that the true relations between physical activity, cognitive performance, and mental health may be**

non-monotonic and heterogeneous across activities, tasks, and mental health measures. These relations can also unfold over much longer timescales than have been previously identified (on the order of months; Fig. 6). However, despite the complexities of the structures of these associations, we also found that they were often remarkably consistent across people. For example, as displayed in Figure S14, many of the associations between fitness, behavioral, and mental health measures were consistent across over 97.5% of 10,000 randomly chosen subsets of participants."

Our intention here is to clarify our findings and claims regarding potential links between physical activity, cognitive (memory) performance, and mental health. Of note, because our study is purely correlational, we cannot gain specific insights into potential *causal* associations between these factors. We have therefore tried to be careful about how we present our findings to avoid implying that we have uncovered new potential interventions or causal factors. Rather, we see our study as contributing three main take-home messages (also copied from our response to Reviewer 1, above):

- **Most prior (primary) studies treat exercise or physical activity as a "binary" variable that participants either engage in (e.g., in an "exercise" or "training" condition) or do not engage in (e.g., in a "control" condition). Our work suggests that the true relations between physical activity, cognitive performance, and mental health may be substantially more complex (e.g., non-monotonic, multivariate, etc.).**
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